Shear strengths of lipped channel beams with stiffened web openings using numerical studies

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ABSTRACT: This paper presents the details of numerical studies on the shear behaviour and strength of lipped channel beams (LCBs) with stiffened web openings. Over the last couple of decades, cold-formed steel beams have been used extensively in residential, industrial and commercial buildings as primary load bearing structural components. Their shear strengths are considerably reduced when web openings are included for the purpose of locating building services. Our research has shown that shear strengths of LCBs were reduced by up to 70% due to the inclusion of web openings. Hence there is a need to improve the shear strengths of LCBs with web openings. A cost effective way to improve the detrimental effects of a large web opening is to attach appropriate stiffeners around the web openings in order to restore the original shear strength and stiffness of LCBs. Hence numerical studies were undertaken to investigate the shear strengths of LCBs with stiffened web openings. In this research, finite element models of LCBs with stiffened web openings in shear were developed to simulate the shear behaviour and strength of LCBs. Various stiffening methods using plate and LCB stud stiffeners attached to LCBs using screw-fastening were attempted. The developed models were then validated by comparing their results with experimental results and used in parametric studies. Both finite element analysis and experimental results showed that the stiffening arrangements recommended by past research for cold-formed steel channel beams are not adequate to restore the shear strengths of LCBs with web openings. Therefore new stiffener arrangements were proposed for LCBs with web openings based on experimental and finite element analysis results. This paper presents the details of finite element models and analyses used in this research and the results including the recommended stiffener arrangements.

1 INTRODUCTION

The use of cold-formed steel members in low rise building construction has increased significantly in recent times. There are many significant benefits associated with the use of lightweight cold-formed steel sections in buildings. Lipped channel and Z-sections are commonly used in low rise building construction due to their high strength-to-weight ratio, economy of transportation and handling, ease of fabrication, simple erection and installation. Figure 1 shows the use of lipped channel beams (LCB) in floor systems with circular web openings.

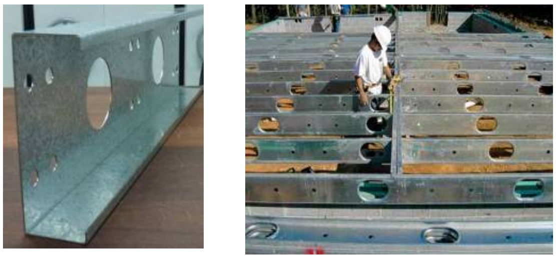


Figure 1. LCBs with web openings.

At present industry applications in flooring systems include openings in the web of floor joists or bearers so that building services such as electrical conduits and plumbing facilities can be located within them. Three standard opening sizes of 60, 100 and 125 mm are used with the currently available LCBs. Shear force is carried by the web element of LCB. Therefore the use of web openings in LCBs significantly reduces their shear capacity due to the reduced web area. There are many variables that affect the shear capacity of members containing web openings. They include the shape, position and size of web openings and also the web slenderness. Hence Keerthan and Mahendran (2012a,c) investigated the shear behaviour and strength of LCBs with circular web openings using experimental and numerical studies. New design equations were developed by them for the shear capacity of LCBs with web openings, which included the effects of enhanced buckling due to the rigid web-flange juncture, and post-buckling strength in shear.

Since the loss of shear capacity of LCBs was found to be as high as 70% (Keerthan and Mahendran, 2012a) when the depth of web opening to clear height ratio (d_{wh}/d_1) was 0.7, there is a need to enhance the shear capacity of LCB with web openings. A cost effective way to enhance the detrimental effects of a large web opening is to attach suitable stiffeners around the web openings. Current cold-formed steel design standards (AISI, 2004, 2007 and SA, 2005) do not provide adequate guidelines to assist the design and construction of stiffeners for LCB floor joists with large web openings. Keerthan and Mahendran (2013) investigated the shear behaviour and strength of LiteSteel beams (OATM, 2008) with stiffened web openings using experimental and numerical studies while Sivakumaran (2008) conducted an experimental study to develop a stiffener system for cold-formed LCBs with web openings. However, limited research has been undertaken to investigate the shear behaviour of LCBs with stiffened web openings. Hence numerical and experimental studies were conducted to develop suitable stiffener arrangements for LCBs with web openings subjected to shear. This paper presents the details of finite element analysis (FEA) based studies of LCBs with stiffened circular web openings, and the results. New plate stiffener arrangements are developed for LCBs to restore the original shear capacity of LCBs without web openings based on test and FEA results.

2 EXPERIMENTAL STUDIES

This section reports the details of the web stiffening arrangements used in Keerthan and Mahendran's (2012d) experimental study. This experimental study was focused on the use of plate stiffeners with varying fastening arrangements to obtain the best fastening method. It was based on a series of primarily shear tests of simply supported LCBs with stiffened web openings subject to a mid-span load (Figure 2). Flanges were restrained by straps to eliminate the flange distortion.

Test specimens of LCBs, 250x75x1.9 LCB and 160x65x1.9 LCB, were considered in the shear tests. Three opening sizes of 60, 100 and 125 mm were selected based on the standard sizes. Plate and stud stiffeners were used with varying thicknesses and sizes and screw fastening arrangements in nine tests. Eight tests were also carried out without stiffening the web openings, giving a total of 17 tests. To simulate a primarily shear condition, relatively short test beams were selected based on two aspect ratios (shear span a/ clear web height d_1) of 1.0 and 1.5. Table 1 shows the details of test specimens while Figure 2 shows the stiffening arrangements used in this experimental study.

No.	LCB Sections	Aspect Ratio	d_w (mm)	d_{wh}/d_1	Type of Stiffeners	Fastening Arrangement	Stiffener Size (mm)	Shear Capacity (kN)	Shear Capacity (%)
1	250x75x15x1.9	1.5	0	0.00	-		-	63.0	100.0
2	250x75x15x1.9	1.5	60	0.24	-		-	61.8	98.1
3	250x75x15x1.9	1.5	100	0.40	-		-	47.8	75.9
4	250x75x15x1.9	1.5	125	0.50	-		-	39.7	63.0
5	250x75x15x1.9	1.5	60	0.24	Plate	A1 (AISI)	110x110x1.9	65.6	104.1
6	250x75x15x1.9	1.5	100	0.40	Plate	A1 (AISI)	150x150x1.9	56.9	90.3
7	250x75x15x1.9	1.5	100	0.40	LCB Stud	A2(Optimum)	250x248x1.9	65.2	103.5
8	250x75x15x1.9	1.5	100	0.40	Plate	A2(Optimum)	200x200x1.9	62.7	99.5
9	250x75x15x1.9	1.5	125	0.50	Plate	A2(Optimum)	225x225x1.9	53.7	85.2
10	250x75x15x1.9	1.5	125	0.50	Plate x2	A2(Optimum)	225x225x3.8	62.2	99.0
11	250x75x15x1.95	1.0	0	0.00	-		-	55.3	100.0
12	250x75x15x1.95	1.0	100	0.40	-		-	34.4	62.2
13	250x75x15x1.95	1.0	125	0.50	-		-	28.1	50.8
14	250x75x15x1.95	1.0	100	0.40	Plate	A2(Optimum)	200x200x1.9	50.6	91.5
15	250x75x15x1.95	1.0	125	0.50	Plate	A2(Optimum)	225x225x1.9	44.2	80.0
16	160x65x15x1.9	1.0	0	0.00	-		-	73.8	100.0
17	160x65x15x1.9	1.0	100	0.63	Plate x2	A2(Optimum)	130x130x3.8	45.3	61.4

Table 1. Test specimen details.

Note: A1- Arrangement 1, A2 – Arrangement 2, d_{wh} = Depth of Web Opening, d_1- Clear Height of Web. For 250x75x15x1.9, f_{yw} = 515MPa For 160x65x15x1.9, f_{yw} = 515 MPa, For 250x75x15x1.95, f_{yw} = 271 MPa

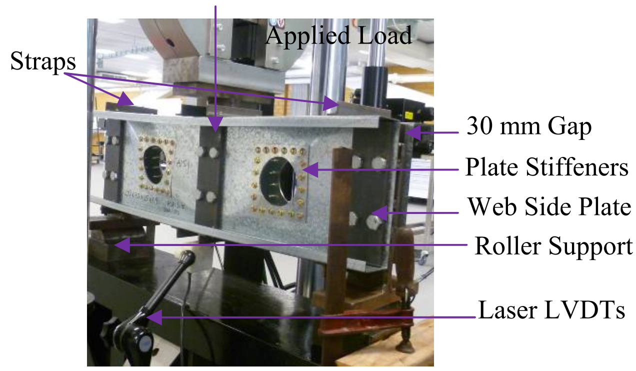
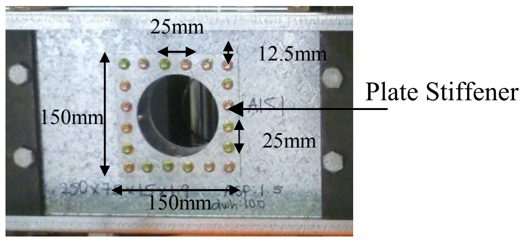
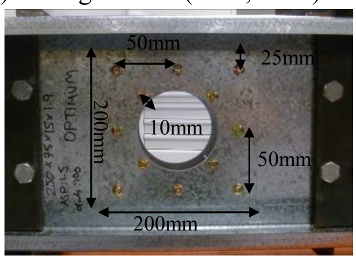


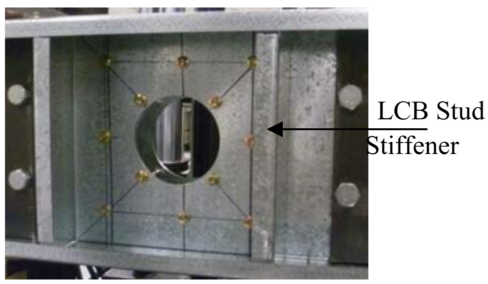
Figure 2. Experimental set-up.



(a) Arrangement 1 (AISI, 2004)



(b) Arrangement 2 (Plate Stiffener)



(c) Arrangement 2 (LCB Stud Stiffener)

Figure 3. Stiffener Arrangements.

Stiffeners were not attached in Test Specimens 1 to 4 (Aspect ratio = 1.5). In Test Specimens 5 and 6, the web openings were reinforced with plate stiffeners based on AISI's (2004) minimum stiffening requirements. The thickness of the plate stiffener was equal to the thickness of 250x75x1.9 LCB section while the plate stiffener extended 25 mm beyond all the edges of the web openings. This provided the dimensions of 110x110x1.9 mm and 150x150x1.9 mm for the plate stiffeners of Test Specimen 5 and 6, respectively. The plate stiffener was fastened to the web of the LCB section with No.12 Tek screws at 25 mm spacing along the edges of the plate stiffener with an edge distance of 12.5 mm as shown in Figure 3 (a). This stiffener arrangement was defined as "Arrangement 1" (AISI, 2004) in this paper.

To investigate the effect of using LCB stud stiffeners on the shear capacity of LCBs with web openings, Test 7 was conducted as shown in Figure 3c. Here 250x248x1.9 LCB stud stiffeners were attached to LCB specimen with 100 mm web openings. The screw fastening arrangement in Test Specimens 7 to 10 was placed with three screws on each side of the plate stiffener giving a total of 8 screws and enhanced with four additional screws in the diagonal direction giving a total of 12 screws (Arrangement 2) as shown in Figures 3b and 3c. The additional screws along the diagonal direction were located at 10 mm from the edge of the web openings. Test Specimen 10 was used to investigate the use of thicker 3.8 mm (two 1.9 mm plate stiffeners) and wider (225 mm) plate stiffeners to restore the shear capacity in the case of larger 125 mm web openings. Stiffeners were not attached in Test Specimens 11 to 13 and 16 (Aspect ratio =1.0). In Test Specimens 14, 15 and 17, the web openings were reinforced with plate stiffeners based on Arrangement 2. Table 1 shows the ultimate shear capacities of the LCBs tested in this study. Details of experimental studies are reported in Keerthan and Mahendran (2012d).

Test Specimen 6 only attained 90% of the shear capacity of LCB section without web openings (56.9 kN vs 63 kN). Therefore this test showed that the plate stiffeners established as per AISI (2004) recommendations are not adequate to restore the shear strengths of LCB with web openings when the ratio of depth of web opening to clear height of web (d_{wh}/d_1) is 0.40.

Experimental results (Table 1) show that by using LCB stud stiffeners with improved Arrangement 2 it was possible to attain 100% of the shear capacity of LCB without web openings (65.2 kN) in Test specimen 7 with 100 mm web openings (d_{wh}/d_1 = 0.40). The use of LCB stud stiffeners (Test Specimen 7, 65.2 kN) provided higher shear capacities than plate stiffeners of the same thickness (Test Specimen 8, 62.7 kN). However, LCB Stud stiffener may not be able to fully restore the shear capacity of LCBs without web openings when the depth of web opening to clear height ratio (d_{wh}/d_1) is greater than 0.40.

Tests 9 and 10 were conducted to determine the required web thickness in the case of larger 125 mm web openings. They were conducted with 1.9 mm and 3.8 mm plate stiffeners that were 225 x 225 mm wide and depth (50 mm on either side of the edge of web openings). Test Specimen 9 only attained 85% of the shear capacity of LCB section without web openings (53.7 kN vs 63 kN). However, Test Specimen 10 attained 99% of the shear capacity of LCB section without web openings (62.2 kN vs 63 kN). These tests thus show that plate stiffeners of appropriate thickness screw-fastened using Arrangement 2 were able to restore the full shear capacity of LCBs.

When compared to Test Specimens 8 and 9 (Aspect ratio = 1.5) which were identical to Test Speciemns 14 and 15, shear capacities attained in Test Specimens 14 and 15 (Aspect ratio =1.0) were slightly lower. This slight reduction in shear capacity is a result of the optimum plate stiffener sizes being reduced for Tests 14 and 15. The aspect ratio of 1.0 meant a smaller shear panel length (a), which led to reduced distance between the web side plates and thus the optimum plate stiffener sizes had to be reduced to fit between the holding plates.

3 FINITE ELEMENT ANALYSES

This section presents the development of suitable finite element models to investigate the ultimate shear behaviour and strength of LCBs with stiffened web openings. For the numerical study, a general purpose finite element program, ABAQUS Version 6.7 (HKS, 2007), which has the capability of undertaking geometric and material non-linear analyses of three dimensional structures, was used. Finite element models were developed to simulate the actual test members' physical geometry, loads, constraints and mechanical properties in the experimental study as reported in the last section. The cross-section geometry of the finite element model was based on the measured dimensions, thicknesses and yield stresses of 17 tested LCBs. Table 1 gives the measured dimensions of the test beams made of 250x75x15x1.9LCB and160x65x15x1.9 LCB sections. The shell element in ABAQUS called S4R5 was used to simulate the shear behaviour of LCBs with stiffened web openings. R3D4 rigid body elements were used to simulate the restraints and loading in the finite element models of LCBs with stiffened web openings. Convergence studies showed that an element size of 5 mm x 5 mm provided an accurate representation of shear buckling and yielding deformations. To obtain accurate results, paver mesh was applied around the LCB web and stiffener openings. Figure 4 shows the geometry and finite element mesh of a typical LCB with stiffened web openings used in this numerical study.

The ABAQUS classical metal plasticity model was used in all the FE analyses. The elastic modulus and Poisson's ratio were taken as 200,000 MPa and 0.3, respectively. Simply supported boundary conditions were applied in the finite element models of LCBs with stiffened web openings. The vertical translation was not restrained at the loading point. Figure 5 shows the applied loads and boundary conditions used in the models. Shear test specimens included a 75 mm wide plate at each support to prevent lateral movement and twisting of the cross-section. These stiffening plates were modelled as rigid bodies using R3D4 elements. Simply supported boundary conditions were applied to the node at the shear centre to provide an ideal pinned support.

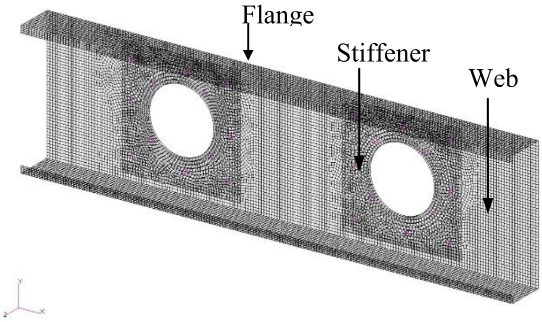
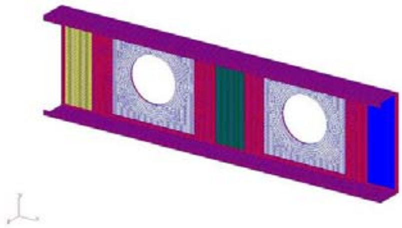


Figure 4. Geometry and finite element mesh of a typical LCB with stiffened web openings (250x75x15x1.9 LCB with 125mm web openings, Aspect ratio = 1.5).

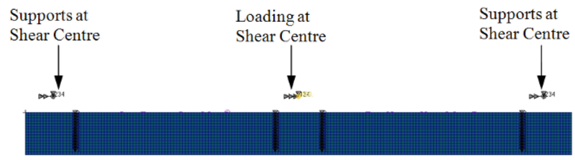
In Keerthan and Mahendran's (2012d) tests, there were no screw fastener failures. Therefore this observation was assumed in all the finite element analyses used here. The screw fasteners connecting the LCB to the stiffeners (Plate or LCB stud stiffeners) were not explicitly simulated in the finite element model. Instead they were simulated using perfect Tie MPCs, which makes all active degrees of freedom equal on both sides of the connection. The fabrication tolerance limit of $0.006d_1$ was used as imperfection in the numerical models of LCBs. It was decided to neglect the residual stresses in the FEA of LCBs with stiffened web openings as the effect of residual stresses on the shear capacity of LCBs with openings is less than 1% (Keerthan and Mahendran, 2012a). Experimental studies (Keerthan and Mahendran, 2012d) showed that strap failures did not occur. Considering this observation, the straps were not explicitly modelled. Instead they were simulated using suitable boundary conditions as follows at strap locations.

$$u_x = 0 \quad u_y = 0 \quad u_z = 1 \quad \theta_x = 1 \quad \theta_y = 0 \quad \theta_z = 0$$

In the above, u_x, u_y and u_z are translations and θ_x, θ_y and θ_z are rotations in the x, y and z directions, respectively, and 0 denotes free and 1 denotes restrained.



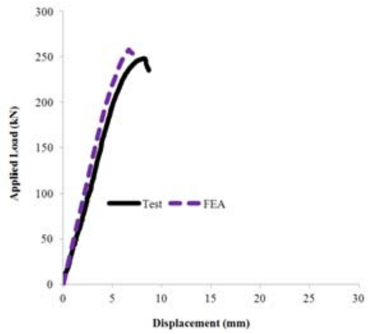
(a) Rigid Body



(b) Plan View

Figure 5. Applied loads and boundary conditions.

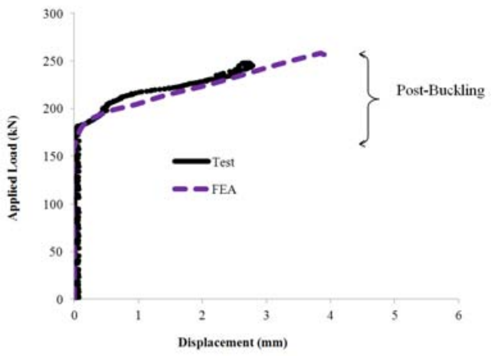
The developed finite element models for non-linear analyses of LCBs with stiffened web openings were validated by comparing the non-linear analysis results with the results obtained from the shear tests (Keerthan and Mahendran, 2012d). This comparison was planned to establish the validity of the shell element model in the modelling of initial geometric imperfections and shear deformations, and associated material yielding. The FEA results were compared with those from testing, with particular attention given to the ultimate load, load-deflection curves and failure mechanisms. Table 2 presents a summary of the ultimate shear capacity results of LCBs with stiffened web openings from FEA and tests. The mean and COV of the ratio of test to FEA ultimate shear capacities are 0.99 and 0.01. This indicates that the finite element model developed in this study is able to predict the ultimate shear capacity of LCBs with stiffened web openings with very good accuracy. Figure 6 shows the FEA results in the form of load versus deflection for 250x75x15x1.9 LCB with 125 mm stiffened web openings (Test Specimen 10) and compare them with corresponding experimental results while Figure 7 shows the shear failure modes of Test Specimen 9. Figures 6 and 7 show a good agreement between the results from FEA and experiments.



(a) Vertical Deflection

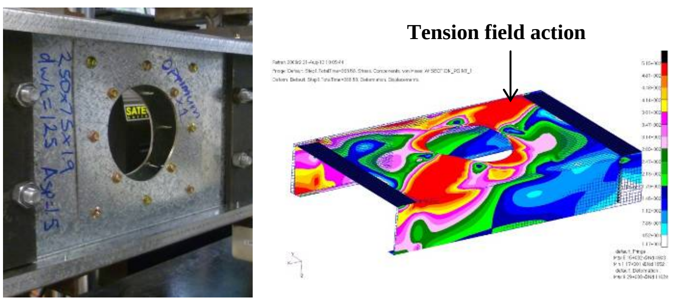
Figure 6. Applied load versus deflections for Test specimen 10.

Figure 6b and 7b confirms that LCBs with stiffened web openings have post-buckling strength due to the presence of tension field action.



(b) Lateral Deflection

Figure 6. Applied load versus deflections for Test specimen 10.



(a) Test (b) FEA

Figure 7: Failure mode of 250x75x15x1.9 LCB with 125mm stiffened web openings and 225x225x1.9 mm plate stiffeners (Test specimen 9).

In summary, FEA and test results in Table 2 show that plate stiffeners with dimensions equal to web opening width and depth plus 100 mm, screw fastened using Arrangement 2, are required to restore the full shear capacity of LCBs.

Table 2. Comparison of FEA and test results (aspect ratio=1.5).

LCB Section	d_{wh}/d_1	t_{stiff}/t_w	Type of Stiffeners	Fastening Arrangement	Stiffener Size (mm)	Shear Capacity Test (kN)	Shear Capacity FEA (kN)	Shear Capacity (%)
250x75x15x1.9	0.00		-		-	63.0	64.0	100
250x75x15x1.9	0.24		-		-	61.8	62.0	97
250x75x15x1.9	0.40		-		-	47.8	48.3	75
250x75x15x1.9	0.50		-		-	39.7	39.9	62
250x75x15x1.9	0.24	1.0	Plate	A1 (AISI)	110x110x1.9	65.6	66.0	103
250x75x15x1.9	0.40	1.0	Plate	A1 (AISI)	150x150x1.9	56.9	57.5	90
250x75x15x1.9	0.40	1.0	Plate	A2(Optimum)	200x200x1.9	62.7	63.0	98
250x75x15x1.9	0.50	1.0	Plate	A2(Optimum)	225x225x1.9	53.7	54.0	84
250x75x15x1.9	0.50	2.0	Plate x2	A2(Optimum)	225x225x3.8	62.2	64.5	101
250x75x15x1.9	0.60	2.0	Plate x2	A2(Optimum)	250x250x3.8	-	66.0	103
250x75x15x1.9	0.70	2.0	Plate x2	A2(Optimum)	275x250x3.8	-	58.5	91
250x75x15x1.9	0.70	2.5	Platex2.5	A2(Optimum)	275x250x4.8	-	66.5	104

5 SUITABLE PLATE STIFFENER SYSTEMS

In this section a suitable plate stiffener system is developed for LCBs with web openings based on test and FEA results. Although shear tests were conducted only for 250x75x1.9LCBs, it is considered that test results reported in this paper can be used to propose a suitable stiffener system that is applicable to other LCBs. FEA and test results showed that LCB stud stiffener was able to fully restore the shear capacity of LCBs without web openings when the depth of web opening to clear height ratio (d_{wh}/d_1) is equal or less than 0.40. Plate stiffeners are proposed with the following minimum dimensions based on FEA and test results. The width of the recommended plate stiffener is d_{wh}+100 mm where d_{wh} is the depth of web opening while its height is lesser of clear web height (d_1) and d_{wh}+100 mm. It is recommended that these plate stiffeners are fastened to LCB webs using No.12 Tek screws and Arrangement 2.

It was found that the required plate stiffener thickness depends mainly on the ratio of the depth of web opening to the clear height of web ratio (d_{wh}/d_1). Therefore suitable predictive equations for the thickness of recommended plate stiffeners (t_{stiff}) were proposed based on d_{wh}/d_1 (Eqns. (1) to (3)). Eqns. (1) to (3) and associated d_{wh}/d_1 ranges were determined based on the test and FEA results reported here.

$$t_{Stiff} = t_w \qquad 0.24 < \frac{d_{wh}}{d_1} \leq 0.40 \tag{1}$$

$$t_{Stiff} = 2t_w \qquad 0.40 < \frac{d_{wh}}{d_1} \leq 0.60 \tag{2}$$

$$t_{Stiff} = 2.5t_w \qquad 0.60 < \frac{d_{wh}}{d_1} \leq 0.70 \tag{3}$$

$$w_{Stiff} = d_{wh}+100 \tag{4}$$

$$h_{Stiff} = \text{Lesser of } d_{wh}+100 \text{ and } d_1 \tag{5}$$

where, t_{stiff}, w_{stiff}, h_{stiff} = Thickness, width and height of plate stiffeners

d_{wh} = Depth of web openings

d_1= Clear height of LCB web element

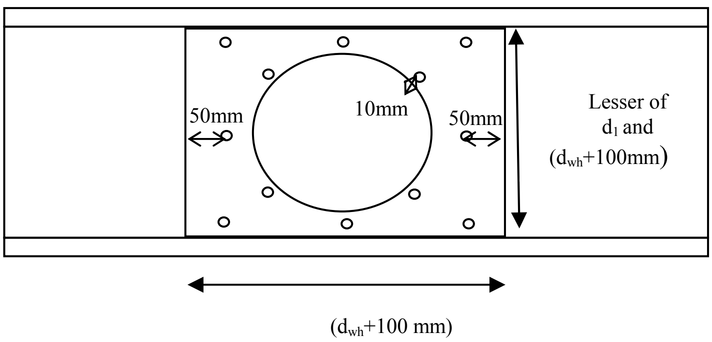


Figure 8. Effective plate stiffener system for LCBs with web openings.

Since the level of fixity at the web-flange juncture of LCB is the same for the available LCBs (23% fixity level) (Keerthan and Mahendran, 2012b), Eqns. (1) to (3) are considered to be applicable to all the LCB sections.

Keerthan and Mahendran (2012b) proposed suitable equations for the shear capacity of LCBs without web openings. These equations can be used for LCBs with stiffened web openings when the improved, recommended stiffener arrangement (Arrangement 2) is used. Figure 8 shows the schematic diagram of the optimum plate stiffener arrangement for LCBs with web openings.

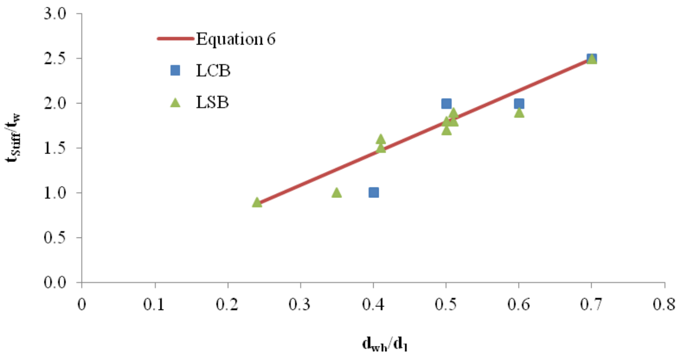


Figure 9. Optimum plate stiffener thickness to web thickness ratio (t_{Siff}/t_w) versus depth of web opening to clear web height (d_{wh}/d_1).

Keerthan and Mahendran (2013) proposed the following equation to predict the thickness of optimum plate stiffeners for hollow flange channel beams known as LiteSteel beams (LSB). Figure 9 includes the results of both lipped channel beams (LCB) and LiteSteel beams (LSB). It shows that Equation 6 can be also used to predict the thickness of optimum plate stiffeners LCBs.

$$t_{Stiff} = \left[3.52\left(\frac{d_{wh}}{d_1}\right) + 0.035\right] t_w \qquad 0.24 < \frac{d_{wh}}{d_1} \le 0.70 \tag{6}$$

4 CONCLUSIONS

This paper has presented the details of a study into the shear performance and strength of lipped channel beams with stiffened web openings. Both experimental and numerical studies were conducted to develop the most suitable web stiffening arrangements for lipped channel beams with circular web openings in shear. To investigate the effects of stiffener types (plate and stud stiffeners) and sizes (thickness, width and height) and screw fastening arrangements on the shear capacities of LCBs with web openings, 17 primarily shear tests were conducted using a three point loading arrangement. Suitable finite element models were then developed and validated by comparing their results with corresponding test results. The developed nonlinear finite element model was able to accurately predict the shear capacities, load-deflection plots and failure modes of LCBs with stiffened web openings. Both numerical and experimental studies show that the plate stiffeners based on the recommendations of AISI (AISI, 2004) are not adequate to restore the shear strengths of LCBs with web openings. New plate stiffener systems with optimum sizes and screw-fastening arrangements were therefore proposed to restore the shear capacities of LCBs with web openings based on the results from both experimental and numerical studies. It was found that the width of the recommended plate stiffener is d_{wh}+100 mm where d_{wh} is the web opening depth while its height is the lesser of clear web height (d_1) and d_{wh}+100 mm. The required stiffener thickness was proposed as a function of the web opening depth to clear web height ratio (d_{wh}/d_1).

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